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The acquired DURIP equipment was used to carry out the research in three projects as summarized below. Our research focussed on experimental realization and information theoretic analysis of quantum cryptosystems. We have introduced and, using the acquired equipment, conducted preliminary experiments on transmission of photon phase information employing frequency division technique suitable for practical realizations over frere space or optical fiber network. The 2-3 order-of-magnitude mismatch between fiber and electronic device capacity can be used to increase the speed, reduce latency, increase ssecurity and reliability in the transmission and distribution of image information. To implement these applications, we used the equipment to construct an all-optical pre-processor at the transmitter and a post-processor at the receiver which performs multiplexing and demultiplexing, respectively. We have been investigating the diffractive optics with multifunctionality in polarization as well as programmable diffractive optics during the last fibe years employing natural birefringent and electrooptic nonlinear materials. Recently we initiated research into artificial dielectric materials (nanostructures) for phhotonic device applications. The acquired equipment also contributed to our characterization effort in the area of artificial dielectrics and diffractive optics.

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Acquired Equipment

1. MIRA 900F, Coherent Inc., modelocked titanium-sapphire source of femtosecond pulses and stabilized He-Ne laser from Spectra Physics Inc. ($97 K).
2. Autocorrelator system from Inrad Inc., ($16 K).
3. Detection systems Newport Corp. and FJW Optical System Inc. (9 K)
4. Oscilloscope from Textronix, Power supplies from Glassman Inc. and HP (7 K)
5. High resolution and wide dynamic range CCD camera with interfaces TEA/CCD-1317K1 with controller, Princeton Instruments Inc. (20 K)
6. Optical table top and support system from Newport Inc. was required to be able installing the lasers (item#1) and set up research experiments ($14 K)
7. High resolution optical spectrum analyzers WA-2500, PZ-91 and RG-93 programmable ramp generator from Burleigh Instruments Inc. ($11 K)
8. Nonlinear $\chi^{(2)}$ and $\chi^{(3)}$ crystals (from Deltronic Crystals and CSK Optronics Corp.) with manipulators (from Newport Corp. and New Focus Inc.) ($20 K)
9. SHG frequency doubler CSK Optronics Corp. ($6 K)
10. High speed phase modulators SSA-128A-900 with SLM2256-128 from Meadowlark Optics Inc., and 10x10 with CTL256 from Displaytech ($ 16 K)
11. Mirrors, lenses and manipulators from Oriel Inc. and Newport Inc. ($ 6 K)
12. Data acquisition and laboratory controller from ATS Inc., Acropolis, etc. ($ 17 K) to interface and control the electronic and electrooptic components of the experiments.

The total cost of the acquired DURIP(95) equipment was $239 K consisting of $199 K provided by the AFOSR DURIP(95) and the $40 K matched by UCSD.

Projects Summary using Acquired Equipment

The acquired DURIP(95) equipment was used to carry out the research in three projects as summarized below.

Robust Quantum and Classical Cryptography for Security and Privacy in Photonic Imaging Network. (Y. Fainman, R. Rao, Y. T. Mazurenko, P. C. Sun, B. Slutsky, L. Shang)

Our research focussed on experimental realization [1-6] and information theoretic analysis of quantum cryptosystems [7-13]. On the theoretical side, we have studied the relationship between the secrecy capacity of a quantum cryptographic system and such factors as the error rate, line attenuation, and detector quality [7-9]. Quantum eavesdropping strategies and possible defenses against them were also investigated [10-13]. We have introduced and, using the acquired DURIP(1995) equipment, conducted preliminary experiments on transmission of photon phase information employing frequency division technique suitable for practical realizations over free space or optical fiber network [1-6]. The advantage of our technique is related to the fact that the phase difference between two signals spectrally separated by a small amount (in our experiments, 80 MHz) is not perceptibly affected by the physical stress to which the fiber carrying them may be subjected. Measurements were performed both with classical strength signals and with photomultipliers used as single photon detectors. Appropriate interfaces between the photomultipliers and the microcomputer controller was also established using the

DURIP(1995) grant. In a separate experiment, we also tested and verified that two signals with frequency sepa-ration of 80 MHz do not experience noticeable phase delay difference due to dispersion in a fiber under external temperature stress. We are currently investigating design and implementation of frequency-division long distance interferometer using all fiber components. We also continue our research on utilizing optical sources that obey sub-Poisson statistics using second order nonlinear optical crystals.

Our second approach uses classical encryption methods for privacy of next generation ultrahigh bandwidth photonic imaging networks. This work explores secure systems that make use of the large optical bandwidth of ultrashort pulses. The technique combines with optical code-division multiple access using stationary or dynamically varying time delays. We have demonstrated few components that are integral part of this system demonstration, including femtosecond laser pulse spectrum modulation using phase-only computer-generated-holograms [14], or a phase-only spatial light modulators. Each encrypted spectrum will be separated into two parts, and transmitted with an appropriately chosen delay between them. Coherent detection uses a complementary spectral-combining device combined with a sequence of temporal delays which allow the selection of the desired transmitter. The designated receiver will be able to compensate for the time-delay of the corresponding transmitter, combine the two complimentary signals, and use the secure phase-decoder to decrypt the message. The coherent detection using three-wave mixing has been also demonstrated using the acquired DURIP(95) equipment [15-19]. The classical encryption system for photonic imaging network privacy employing spread spectrum techniques is currently constructed.

<u>Optical Signal Processing with Femtosecond Pulses</u> (Y. Fainman, Y. T. Mazurenko, P. C. Sun, K. Oba, and D. Marom)

The bandwidth and the efficiency of optical communication systems exceed these of electrical cable systems. Electronic devices and systems connected to optical networks may reach bit-rates on the order of 1-10 Gb/s. In contrast, the maximum bit-rate of a photonic network may exceed 1 Tb/s. The 2-3 order-of-magnitude mismatch between fiber and electronic device capacity can be used to increase the speed, reduce latency, increase security and reliability in the transmission and distribution of image information. To implement these applications, we used the acquired DURIP(95) equipment to construct an all-optical pre-processor at the transmitter and a post-processor at the receiver which performs multiplexing and demultiplexing, respectively [20-25]. The multiplexer performing image space-to-time transformation combines relatively slow but parallel in space electronic channels into an ultrahigh bandwidth serial optical channel (i.e., parallel-to-serial conversion), whereas the demultiplexer performs the inverse time-to-image space transformation for processing and/or electronic detection (i.e., serial-to-parallel conversion). For efficient bandwidth utilization, these processors need to be operated at rates determined by the bandwidth of the optical pulses [26]. Such space-time optical processors have been constructed using the equipment from this grant and applied for pulse shaping, filtering, and space-to-time multiplexing and time-to-space demultiplexing [20, 21, 27, 14-17].

Another example of using the acquired DURIP(95) equipment exploits applications that will benefit from an optical memory that will store and retrieve information in a format that is suitable for direct interface and transmission through an optical network, thereby, providing optimal performance in terms of hardware complexity, memory and network capacity, bandwidth, and latency. In this example we convert spatial image information into time domain. The corresponding data sequence in time is stored employing spectral domain 3-D volume holographic recording [18]. When the stored data is read out of the spectral domain storage system, the output spectrum is converted back into time sequence and sent through the all-optical fiber network to the user node. At the user node the time sequence is converted to

lower rate parallel channels in space domain for optical or electronic filtering and detection [17, 19].

In summary we introduced, analyzed and, using the acquired DURIP(95) equipment, evaluated experimentally a femtosecond pulse storage and imaging techniques useful for demultiplexing and parallel processing sequences of femtosecond pulses. Our pulse imaging method, based on 3-wave mixing in nonlinear crystals, allows converting complex amplitude of an ultrashort temporal pulse signal to a corresponding spatial image that resembles the temporal signal in space. Unlike the commonly used autocorrelator, our method carries both amplitude and phase information of the pulses. We also demonstrate nonvolatile storage of femtosecond pulses in photorefractive $LiNbO_3$ by recording and readout of spectral holograms at a wavelength of 460 nm and 920 nm, respectively. No degradation was observed after 24 hours readout. The demonstrated spectral domain nonvolatile holographic storage and the femtosecond pulse imaging are useful for broadband information systems applications.

Artificial dielectrics and diffractive optics with multifunctionality in polarization and color
(Y. Fainman, F. Xu, P. C. Sun, J. Thomas, R. Tyan, P. Shames, W. Nakagawa, P. Lin)

We have been investigating the diffractive optics with multifunctionality in polarization [28-32 and color [33-35] as well as programmable diffractive optics [36-43] during the last five years employing natural birefringent and electrooptic nonlinear materials. Recently we initiated research into artificial dielectric materials (nanostructures) for photonic device applications. The acquired DURIP(95) equipment also contributed to our characterization effort in the area of artificial dielectrics and diffractive optics. Modern microfabrication techniques (dry etching, electron beam lithography, patterned regrowth, epitaxial growth, laser assisted growth, laser ablation, etc.) allow to artificially fabricate sub-micron micro-structures which modify the dielectric and semiconductor properties such as birefringence, optical nonlinearity or opto-electronic interactions. For example, form birefringence or artificial birefringence effect occurs due to periodic microstructure boundary between two isotropic dielectric materials with different dielectric constants . The form birefrigent microstructures posses several unique properties that make them superior compared to these of naturally birefrigent materials: (i) high strength of form birefringence, $\Delta n/n$, can be obtained by selecting substrate dielectric materials with large refractive index difference (here Δn and n are the difference and the average effective indices of refraction for the two orthogonal polarizations, respectively), (ii) the magnitude of form birefringence, Δn, can be adjusted by varying the duty ratio as well as the shape of the microstructues, (iii) form birefringence can be constructed using an isotropic as well as anisotropic substrate, allowing to fine tune the anisotropic properties of naturally birefringent materials, and (iv) form birefringent microstructures can be used to modify the reflection properties of the dielectric boundaries. The artificial dielectric anisotropy due to form birefringence [44, 45] has been used to construct polarization optics components as well as polarization selective computer generated holograms [46, 47]. The form birefringence and the form birefringent computer generated holograms were characterized experimentally using the acquired DURIP(95) equipment.

We further extend this approach by designing a new device that uses unique properties of anisotropic spectral reflectivity (ASR) characteristics of a high spatial frequency multilayer binary grating [48, 49]. The ASR mechanism is based on combining the effects of the form birefringence of a high spatial frequency grating (i.e., grating period is much less than the wavelength of the incident field) with the resonant reflectivity of a multilayer structure. With our approach, the angular field and wavelength range have been largely increased compared to conventional polarization selective beam splitter (PBS) devices. The ASR PBS combine such unique features as compactness, compatibility with semiconductor materials, negligible insertion

losses, polarization selectivity for light at normal incidence, high polarization extinction ratios, and operation with waves of large angular bandwidth and from broad spectral range. Some interesting characteristics of the element with ASR characteristics cannot be found in a conventional PBS component. For instance, when our ASR device is designed to operate with normally incident light, it acts as a highly efficient polarization selective dielectric mirror [50-53]. The ASR devices have been fabricated and characterized using the acquired DURIP(95) equipment. Furthermore, our ASR device fabrication method is compatable with conventional microfabrication and can become easily integrable with other photonic devices such as VCSELs, MQW modulators, and photodetectors. Initial experiments with fabricated devices demonstrate good performance.

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